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A Proposal to Demonstrate Production of Salad Crops in the Space Station Mockup Facility with Particular Attention to Space, Energy, and Labor Constraints

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SUMMARY

The Salad Machine Research has continued to be a two path effort with the research at Marshall Space Flight Center (MSFC) focusing on the design, construction, and operation of a semiautomated system (Salad Machine) for the production of salad vegetables within a standard rack. Boeing corporation, in cooperation with NASA MSFC and in consultation with Dr. Brooks has constructed a four drawer Salad Machine which has occasionally been placed within the Space Station Freedom Mockup facility for view by selected visitors. Final outfitting of the Salad Machine is awaiting the arrival of parts for the nutrient delivery system. Research at the Alabama A&M facilities has focused on compatibility of radish and lettuce plants when grown on the same nutrient solution Lettuce fresh weight shoot yield was significantly enhanced when lettuce plants were grown on nutrient solution which was shared with radish. Radish tuber production was not significantly affected although there was a trend for radish from shared solutions to be heavier than those grown on separate nutrient solutions. The effect of sharing nutrient solutions on

carbohydrate partitioning reflected the effect of sharing solution on fresh weight yield. Lettuce shoot dry weight was significantly greater for plants from shared solutions than from separate. There was no significant effect of sharing nutrient solution on radish tuber dry weight. Partitioning of nitrogen, calcium, magnesium, and potassium was not affected by sharing, there was, however, a disproportionate amount of potassium in the tissues, suggesting luxury consumption of potassium in all plants and tissues. We conclude from this research that lettuce plants benefit from sharing nutrient solution with radish and that radish is not harmed.

Introduction

During the last 18 months.research at the Alabama A&M facilities has focused on compatibility of radish and lettuce plants when grown on the same nutrient solution Radish and lettuce were chosen as the first pair of crops to be evaluated for compatibility since they both have relatively short growing periods and would allow for rapid turnover of experiments while the graduate student was becoming familar with hydroponic techniques. The previous report detailed these earlier experiments in which electrical conductivity was used as a measure of the nutrient status of the solution and the many problems associated with use of this method in a continuously-used nutrient solution. This report will focus on later experiments in which nutrients were replaced based on solution uptake and a formulation for replacement of nutrients based on those developed by Wheeler et. al (9).

Materials and Methods

'Red Prince' radish and 'Waldmanns Green' lettuce plants were grown in a walk-in growth chamber on an NFT hydroponic system as described previously (Annual report June 1992). The environmental conditions included aerial temperature of 25^{o}C, root solution temperature of 27^{o}C, nutrient solution flow rate of 1l/min, 75% humidity , and continuous lighting from coolwhite flourescent lamps (250 μmole/s/m^2 for exp 1 and 350 μmole/s/m^2 for exp 2). The initial concentrations of the nutrients in

Table 1. Initial elemental concentration of the nutrient solution at the start of each experiment.

Salts	Elemental conc. in ppm						
	N	P	K	Ca	Mg	S	Fe
$Ca(NO_3)_2$	70			100			
kNO_3	30		97				
$MgSO_4$					24	24	
KH_2PO_4		15	19				
Sequestrene™							5
Total	105	15	116	100	24	24	5

Table 2. Concentration and amount of nutrients used in replenishment stock solutions.

Salt	Stock conc. (Mol/L)	Biweekly replenishment (ml of stock added per liter water lost from the NFT system).
$Ca(NO_3)_2$	1.0	1.5
KNO_3	1.0	5.2
KH_2PO_4	1.0	0.9
$MgSO_4$	1.0	0.7
Micronutrients	*	1.8

* Final micronutrients concentrations and ratios according to resp. Hoagland and Arnon (1950).

Fig. 1. Lettuce Shoot Fresh Weight

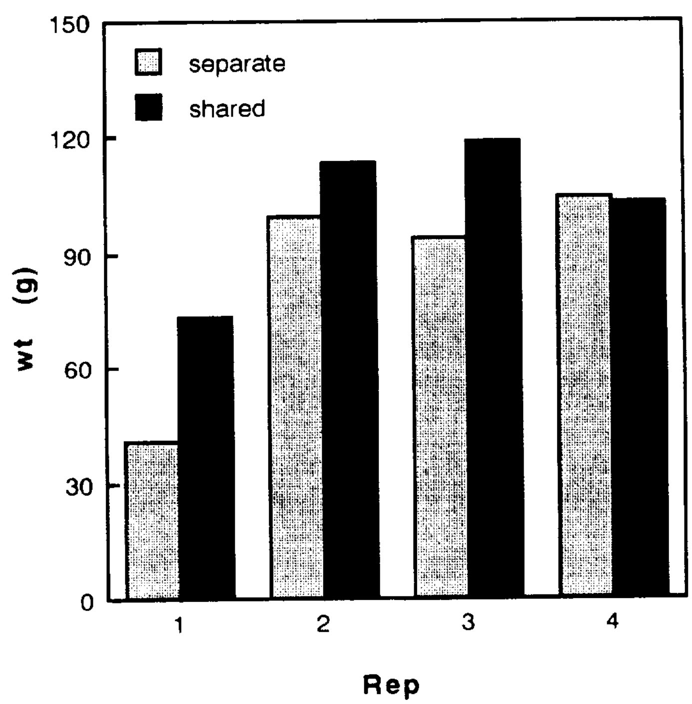


Fig. 2. Lettuce Shoot Fresh Weight Yield, exp. 2

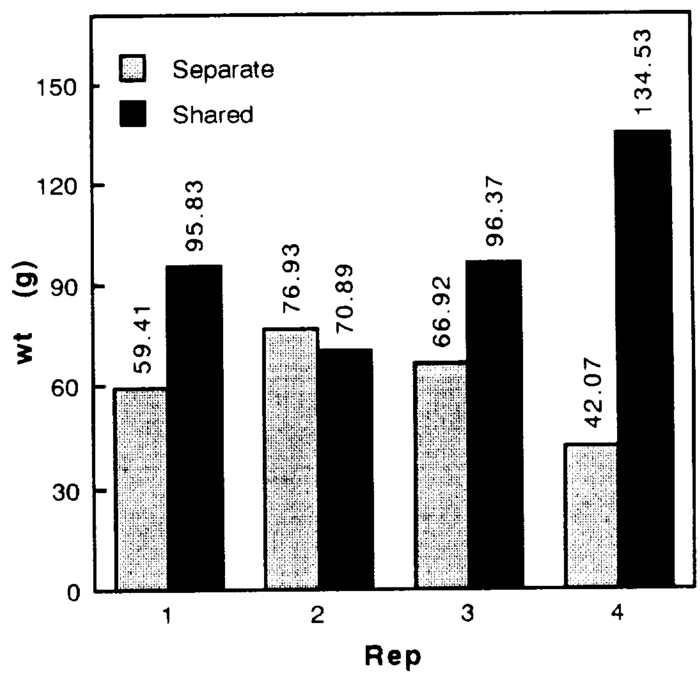


Fig. 3. Radish Fresh Weight Yield, Exp. 1.

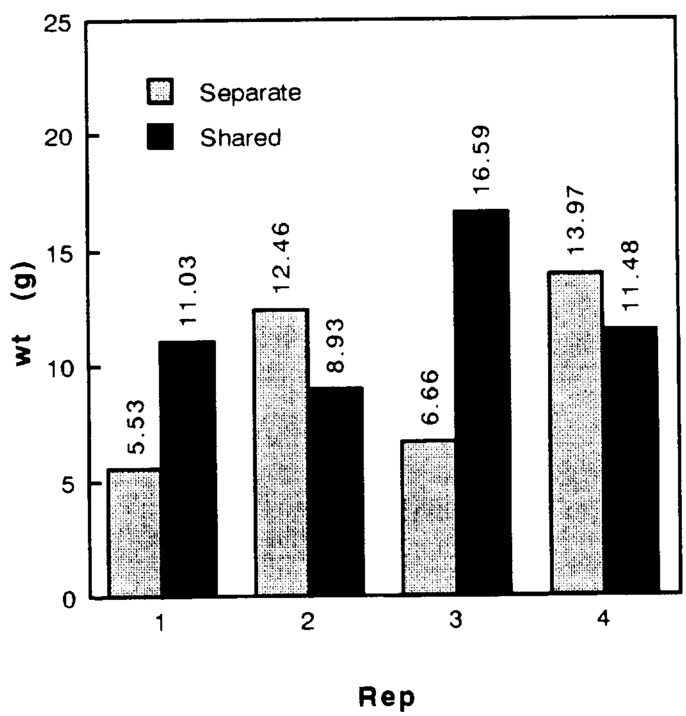
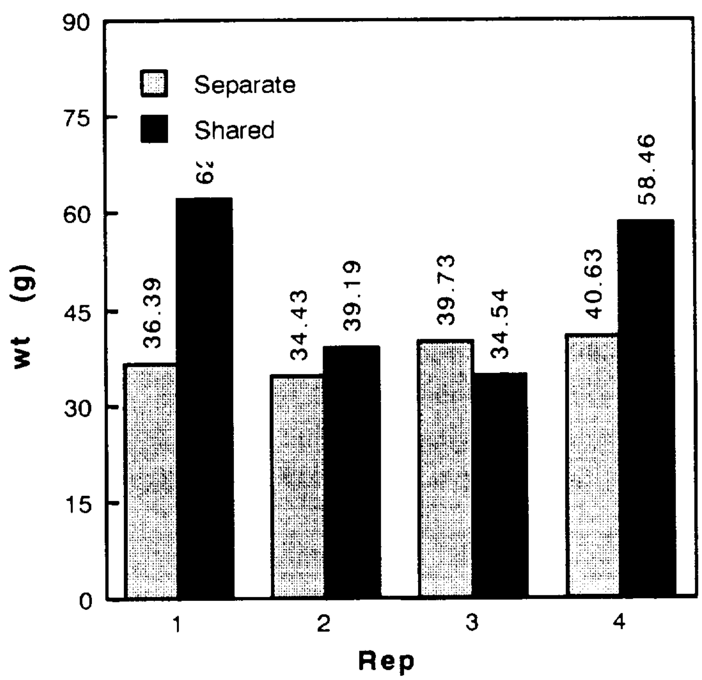


Fig. 4. Radish Fresh Weight Yield, Exp. 2.



the solution at the start of the experiments is presented in Table 1. Nutrients were supplemented as nutrient solution was taken up by the plants with the nutrient concentrations listed in Table 2 for the first experiment. Since a build up of several nutrients after the first two weeks of growth was observed in the first experiment the concentration of supplemental nutrients was decreased by half after the first two weeks of growth for the second experiment.

Results and Discussion

The Effect of Sharing Nutrient Solution on Yield of Lettuce and Radish.

In both trials lettuce yield was signifcantly greater when nutrient solution was shared with radish than when lettuce was grown alone (Figs. 1&2). Lettuce grown on shared nutrient solutions were on average 15 g heavier than lettuce plants grown on separate nutrient solutions in exp 1 (Fig. 1) and 30 g heavier per plant in exp 2 (Fig.2). Radish yield was not significantly affected by sharing nutrient solution with lettuce although there was a trend for radish plants which shared nutrient solution to have greater yields than radish which were grown on separate nutrient solutions (Figs.3 & 4 show rep of rad exp 1 and 2 shared vs separate). Three of four reps in exp one had greater radish yields when radish was grown on nutrient solution that was shared with lettuce. The fourth rep showed very little difference in radish yield between shared on separate nutrient solutions (Fig. 3). Similar results occurred in experiment 2 (Fig. 4). Although the differences in radish growth were not significant at the

5% level it is clear that under suitable nutrient conditions growth of lettuce with radish is not detrimental to radish and is beneficial to lettuce.

Lettuce yields were within the range of yields reported for leaf lettuce grown under similar conditions. Prince et al.(7) reported yields ranging from 72 gfw to 114 gfw under 250 μmole/m2/s PAR for 34 day old plants. Our yields averaged 85 gfw for lettuce plants grown on separate nutrient solution and 102 gfw for plants grown on shared nutrient solution for exp. 1. For exp.2 yields were similar, with an average of 61 gfw per plant for lettuce grown on seperate nutrient solution and 99 gfw for those plants grown on shared solution. Anderson and Nielson (1) report average yields of 127 gfw for lettuce plants transfered to NFT hydroponics system at the 3 to 4 leaf stage and then harvested after 34 days.

The Effect of Sharing Nutrient Solution on Carbohydrate Partitioning.

In addition to determining the effect of sharing nutrient solution on fresh weight yield, a parameter which is most important to achieving the goals of a Salad Machine, we also investigated the effect of sharing nutrient solution on carbohydrate and nutrient partitioning. In exp.#1 there were significant differences between the carbohydrate partitioning of lettuce grown on separate reservoirs and on shared reservoirs (Table 3). As

Table 3. Effect of sharing nutrient solution on carbohydrate partitioning of lettuce.

Exp.#	Treatment	Dry weight shoot	Dry weight root	shoot/root	Edible biomass Index
1	separate	5.34 a*	0.41 a	14.70 a	91.92 a
	shared	6.58 b	0.34 a	23.15 b	95.03 b
2	separate	3.52 a	0.37 a	17.49 a	91.08 a
	shared	5.25 a	0.29 a	23.35 a	94.55 a

* Means followed by the same letter are not significantly different at $p=0.05$ as tested by Tukey's test.

expected from the fresh weight yield results presented in Figures 1&2 lettuce grown on shared reservoirs had a significantly greater shoot dry weight than those grown on separate reservoirs in both experiments (Table 3). Lettuce grown on shared reservoirs had 16% more shoot dry weight than that of lettuce grown on the separate reservoirs.. In exp.#2 the shoot dry weight of lettuce from the shared reservoirs was 32% more than the separate reservoirs. Lettuce root dry weight was significantly greater for plants grown on separate reservoirs than from shared ones. There was no significant effect of sharing nutrient solution on radish tuber dry weight in exp 1 but there was a significant increase in dry weight of radish tuber grown on shared solution relative to separate solution in exp 2. (Table 4). Edible Biomass Index (E.B.I.) is also an important parameter from a CELSS perspective since any non-edible biomass must be processed as waste. The E.B.I. for lettuce was high, in all cases above 90% (Table 3) , which means that at least 90% of the lettuce dry matter was edible. As with lettuce shoot fresh weight, there was a trend for E.B.I. to be higher for shared reservoirs than for separate reservoirs. E.B.I. for radish ranged from 30 to 48 % (Table 4). E.B.I. for radish was calculated with the assumption that the radish tuber is the only part of the radish plant which will be consumed. It is possible,, however, to eat the leaves of radish provided they are processed by cooking like mustard or collard greens. Again, E.B.I. for radish from shared reservoirs was greater than that from separate reservoirs in both experiments.

Table 4. The effect of sharing nutrient solution on carbohydrate partitioning of radish.

Exp.#	Treatment	Dry weight shoot	Dry weight radish	Dry weight root	Shoot/Radish	Edible biomass index
1	separate	1.05 a*	0.69 a	0.17 a	2.32 a	33.67 a
	shared	1.38 b	0.84 a	0.22 a	2.15 a	33.50 a
2	separate	3.56 a	2.63 a	0.45 a	1.72 a	39.42 a
	shared	3.07 a	3.12 a	0.36 a	1.05 a	47.47 b

* Means followed by the same letter are not significantly different at $p=0.05$ as tested by Tukey's Test

The Effect of Sharing Nutrient Solution on Elemental Partitioning

Elemental analysis of dried tissues from exps 1&2 revealed no significant effect of sharing nutrient solution on elemental partitioning. Nitrogen content ranged from 2.75 % to 4.39 % on a dry weight basis (Table 5). Lettuce leaf tissue averaged around 2.8 % nitrogen while radish shoot tissue was 4.2 % on average. Partitioning of Ca and Mg was also not affected by sharing of nutrient solution (Tables 6&7) Calcium and Magnesium content ranged from 0.86 % to 3.77 % for calcium and 0.41 % to 1.97 % for Mg with a tendency for leaf tissues to have higher Ca and Mg content than root tissues. Potassium content ranged from 11.3 % to 24.8%, and again the higher concentrations were present in the leaf tissues versus the root tissues (Table 8). The high concentrations of K relative to the other minerals suggested that luxury consumption of K was occurring. A review of the literature showed that the K content was much higher than that reported previously for lettuce and radish. Potassium concentration of hydroponically-grown lettuce shoots has been reported to be 2.41 % on a dry weight basis (4).and radish shoot K content has been reported to range from 3.62 % (2) to 4.44 % on a dry weight basis. Radish root K concentration has been reported to be 6.6 % (5).

Comparison of Yield Between Exp 1&2

Table 5. Total nitrogen partitioning in lettuce and radish plants grown in separate and shared troughs.

		% N per dry weight				
		Lettuce		Radish		
Exp.	Treatment	shoot	root	shoot	hypocotyl	root
	separate	2.92a*	2.75a	4.08a	3.23a	3.08a
1	shared	2.78a	3.00a	4.02a	3.21a	3.06a
	separate	2.82a	2.77a	4.39a	2.98a	3.36a
2	shared	2.76a	2.92a	4.12a	2.91a	3.18a

*Means of each column followed by the same letter are not significantly different ($p=0.05$) according to LSD test.

Table 6. Ca partitioning in lettuce and radish plants grown in separate and shared troughs.

		% Ca per dry weight				
Exp	Treatment	Letsh	Letrt	Radsh	Rad	Radrt
	separate	3.77a*	1.10a	3.95a	1.05a	2.60a
1	shared	3.11a	2.40a	3.00a	1.87a	2.63b
	separate	1.21a	1.20a	3.80a	0.86a	1.91a
2	shared	1.73a	2.94a	3.31a	1.40a	1.79a

*Means of each column followed by the same letter are not significantly different ($p=0.05$) according to LSD test.

Table 7. Magnesium partitioning in lettuce and radish plants grown in separate and shared troughs

		%Mg per g dry weight				
		Lettuce		Radish		
Exp.#	Treatment	shoot	root	shoot	hypocotyl	root
	separate	1.03a*	1.00a	1.97a	1.10a	1.60a
1	shared	0.45b	1.05a	1.60a	1.30a	1.23a
	separate	0.53a	0.52a	0.79a	0.43a	0.51a
2	shared	0.45a	0.73a	0.65a	0.42a	0.41a

* Mean of each column follower by the same letter are not significantly different ($p=0.05$) according to LSD test.

Table 8. Potassium partitioning in lettuce and radish plants grown in separate and shared troughs.

		% K per dry weight				
Exp	Treatment	Letsh	Letrt	Radsh	Rad	Radrt
	separate	21.0a*	14.5a	18.0a	13.8a	11.3a
1	shared	22.0a	16.5a	24.8a	15.8a	11.3a
	separate	18.8a	13.5a	18.8a	20.8a	14.0a
2	shared	18.6a	15.1a	18.6a	17.7a	9.4a

*Means of each column followed by different letters are signigicant ($p=0.05$) according to LSD test.

Since exp 1&2 differed slightly in protocol (decrease in amount of supplementation in exp 2 due to excess build-up observed in exp 1 and increase in light intensity due to change-out of old lamps for new between exps. 1&2 due to failure of several lamps.) we compared yields in the two experiments. The most notable difference was an increase in radish yield in experiment 2 (Table 9). There was a 400% increase in radish tuber fresh weight yield in experiment 2 relative to experiment 1 whereas there was only an 8 % decrease in lettuce yield in experiment 2 relative to experiment 1. Such a dramatic increase in radish yield from one experiment to the next caused us to wonder what factors may have had the most influence on this increase in yield. One possible factor is the differences in nutrition. Earlier preliminary experiments (data shown in June 1992 report) had shown a difference in lettuce and radish yield with different nutrient concentrations. Lettuce growth was doubled when a nutrient solution containing 13.5 mM nitrogen with part of the nitrogen in the form of NH_4 was used compared to lettuce grown on a nutrient solution containing 6.4 mM NO_3. However, radish growth was 10 fold greater when grown on the solution containing only 6.4 mM NO_3 as the source of nitrogen. A look at the nutrient solution status throughout the two experiments revealed no major deficiencies. Mean nitrate levels in experiment 1 and 2 were 500 ppm $\pm$ 100 ppm throughout the experiments (Fig. 5a, 5b) Phosporous was steady at approximately 12 ppm (Fig. 6) During experiment 1 potassium stayed at 150 ppm except for the third week when levels rose to 200 ppm (Fig. 7a). During experiment 2 potassium concentration stayed steady at approximately 200 ppm (Fig. 7b). Calcium levels were around 80 ppm for the first two weeks of experiment 1 and then rose to approximately 225 ppm for the last two

Table 9. Yield comparison of lettuce and radish grown in separate and shared troughs.

Exp	Treatment	Letsh fw (g)	Rad fw (g)	Total (g)
	separate	85*	12	97
	shared	102	10	112
1	total	187	22	209
	separate	79	38	116
	shared	94	49	143
2	total	173	87	259

* Data represents mean weight per plant.

Fig. 5a. Nitrate levels of Nutrient Solution, Exp. 1.

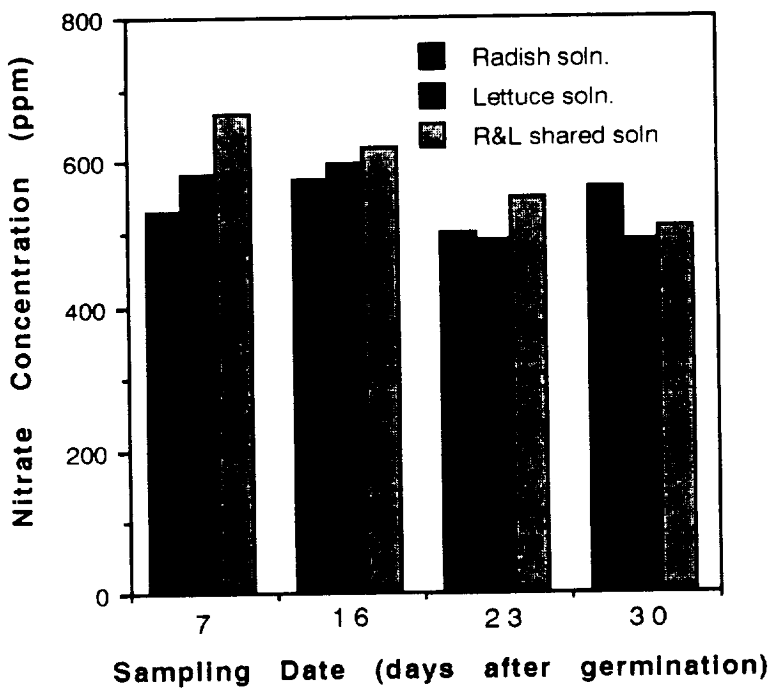


Fig. 5b. NO3 Levels in Nutrient Solution

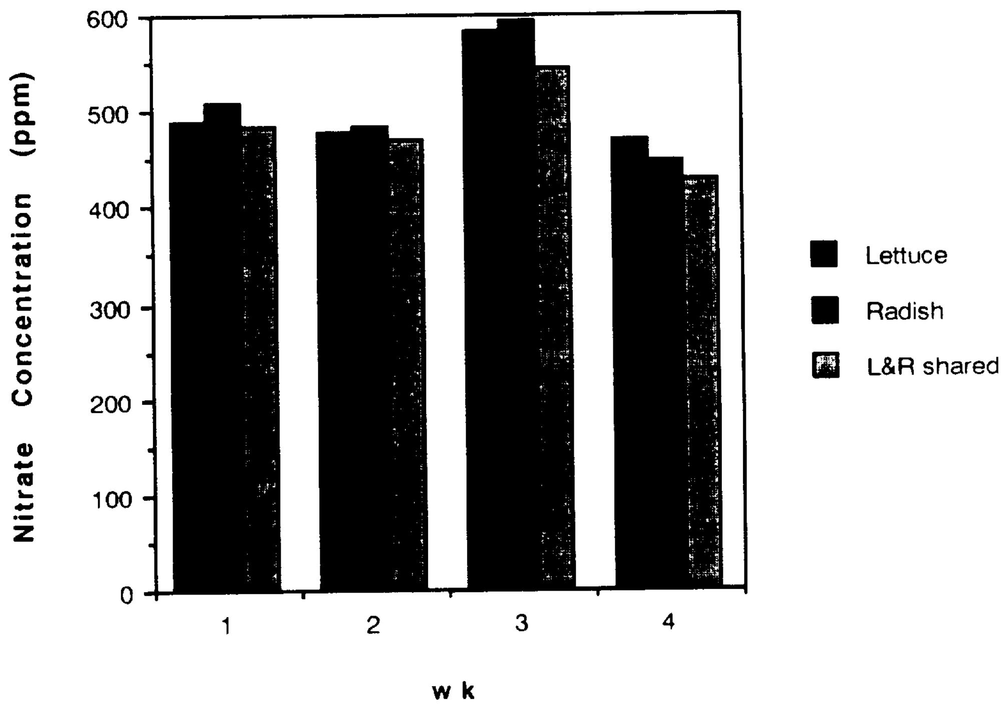


Fig. 6. Nutrient Solution PO4 Levels, Exp. 2.

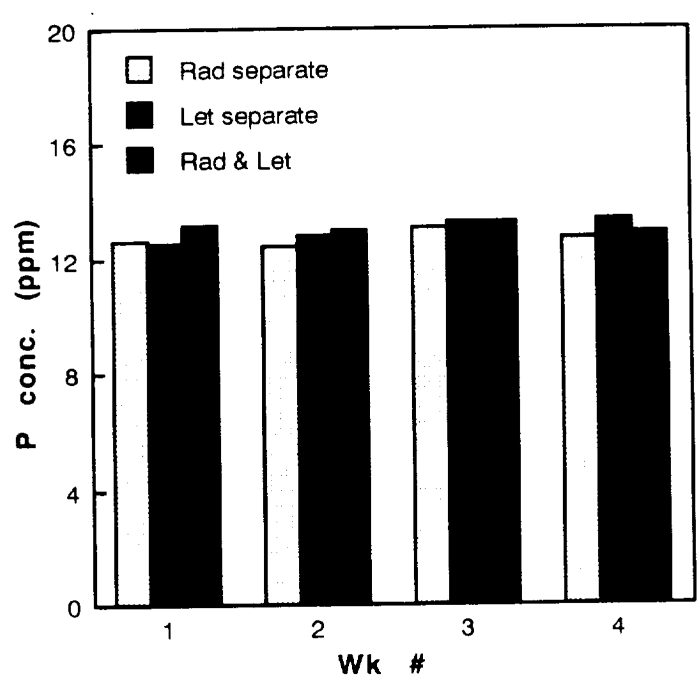


Fig. 7a. Nutrient Solution K Levels, Exp. 1.

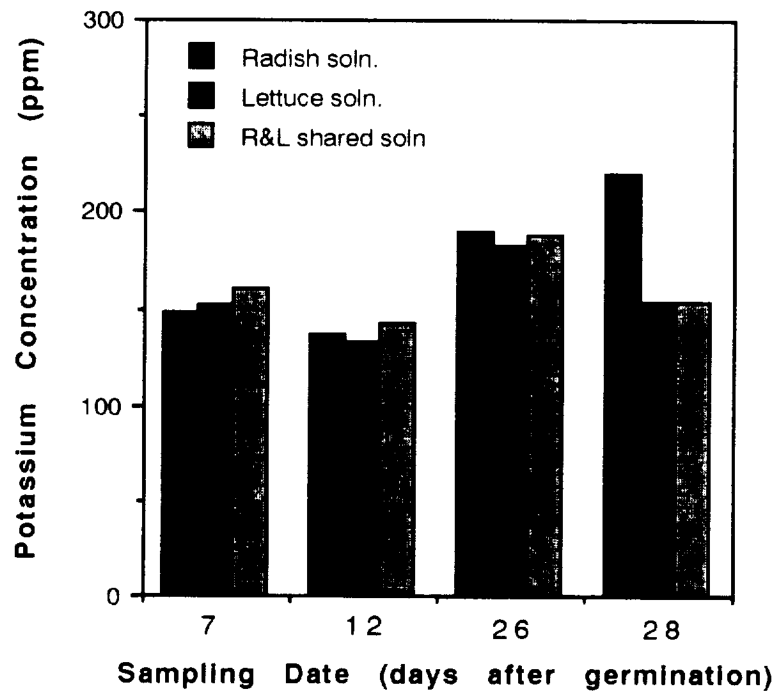
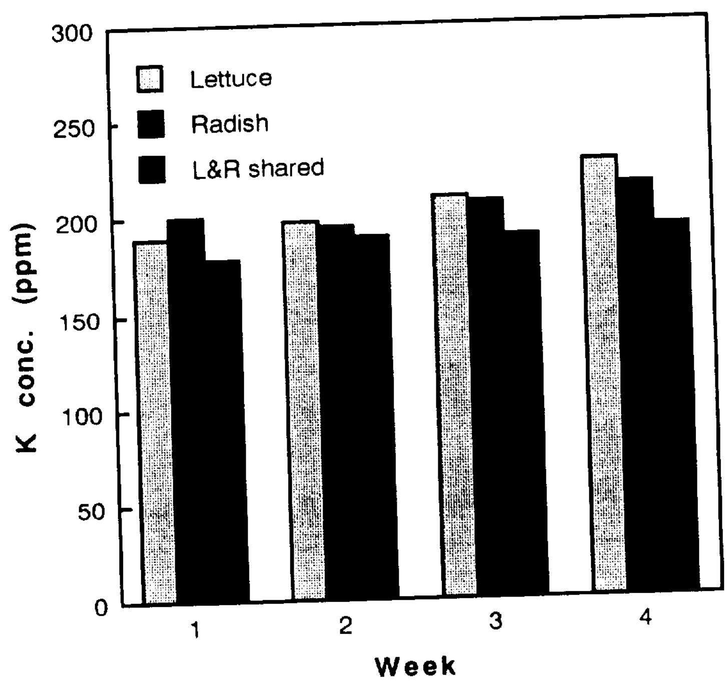


Fig. 7b. Nutrient Solution K Levels, Exp. 2.



weeks (Fig. 8a). Calcium levels were slightly lower in experiment 2 and started in the range of 65-80 ppm and rose to 80 ppm by the third week (Fig. 8b). Magnesium levels differed in experiment 1 &2. During experiment 1 magnesium concentrations started at 20 ppm for the first two weeks and then doubled for the next two weeks (Fig. 9a). During experiment 2 magnesium levels were near 20 ppm for the first two weeks and then dropped off slightly to approximately 15 ppm for week three and 12 ppm for week 4 (Fig. 9b) Iron ranged from 3.5 to 6.0 ppm during the course of the experiment (Fig. 10). While there are some small differences in nutrient levels between the two experiments there was no obvious deficiency or excess which would clearly point to a difference in nutrition causing such a dramatic increase in radish yield in experiment 2.. There also was no obvious trend in nutrient uptake as the elemental analysis of the dried tissues revealed (Tables 5-8). Another possible cause of the difference in yield could be in the icreased light energy available. Radish has been shown to be sensitive to increases in light intensity. Craker and Siebert (3) reported on average a 28% increase in radish root yield for every doubling of light intensity, starting at 14.1 W/m^2 and continuing up to 113.0 W/m^2. Experience with growing radish in the SM also showed it to be very sensitive to light intensity.

It was interesting that the difference in light intensity had no effect on lettuce yield. This could be due to cultivar insensitivity to light intensity. Knight and Mitchell (6) reported that the 'Bibb' cultivar of lettuce was insensitive to an increase of 463 $\mu moles/m^2/s$ of PAR. Growth of 'Salad Bowl' lettuce however increased by one third when grown under 918 $\mu moles./m^2/s$ compared to growth under 455 $\mu moles/m^2/s$. Tibbits et al (8) found little or no effect on dry weight yield of grand

Fig. 8a. Nutrient Solution Ca Levels, Exp. 1.

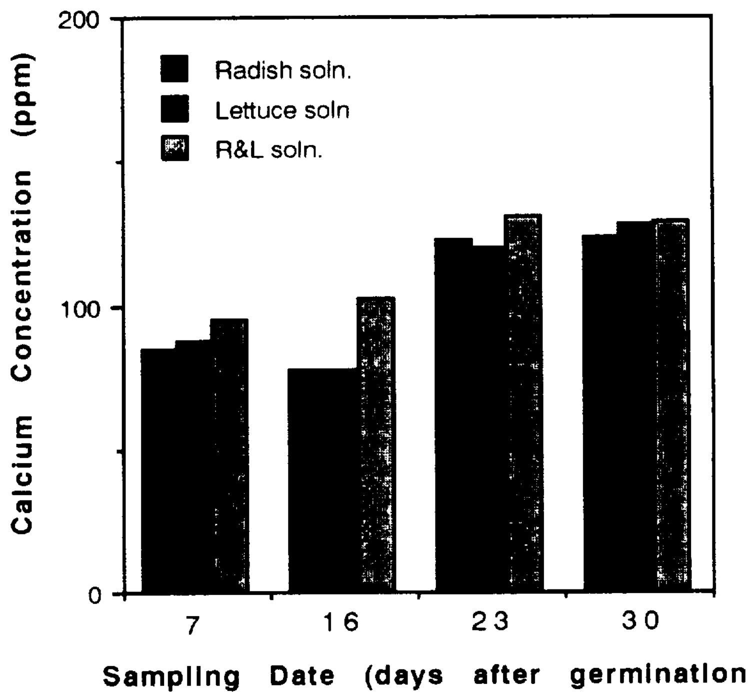


Fig. 8b. Nutrient Solution Ca levels, Exp 2.

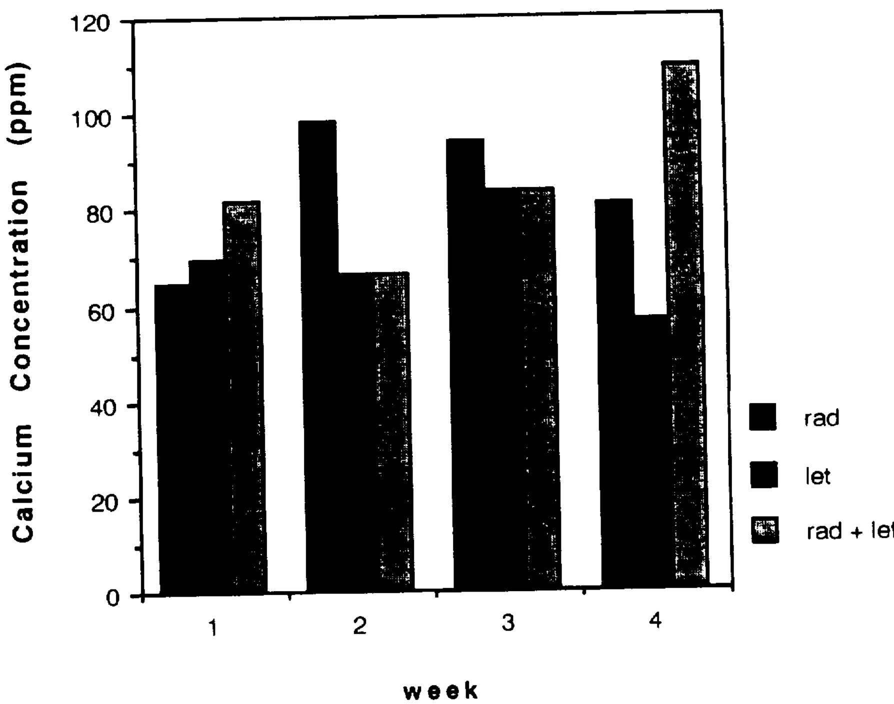


Fig. 9a. Nutrient Solution Mg Levels, Exp1.

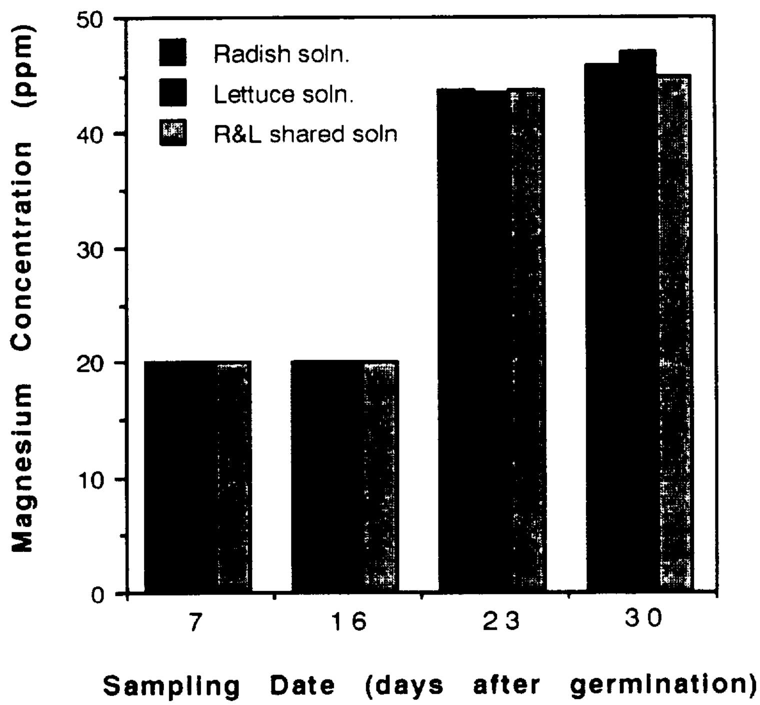


Fig. 9b. Nutrient Solution Mg Levels, Exp. 2.

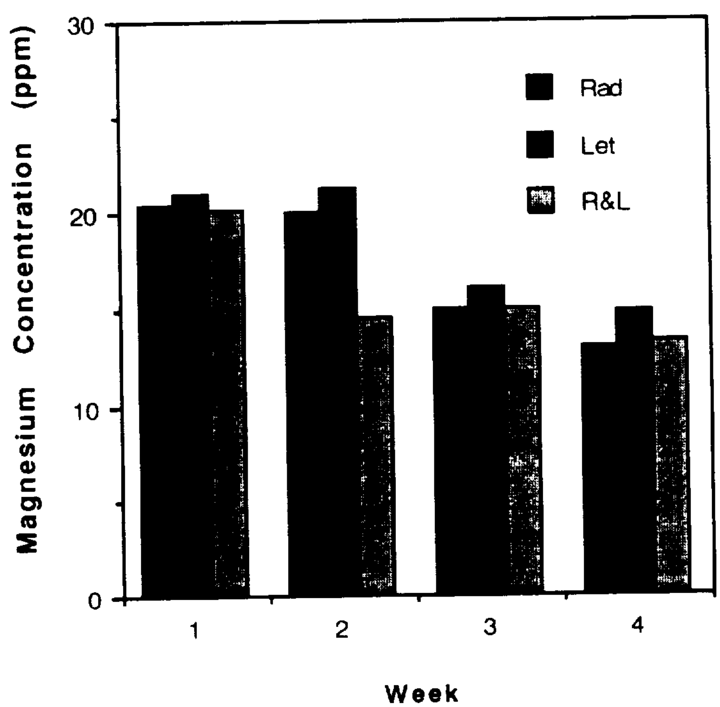
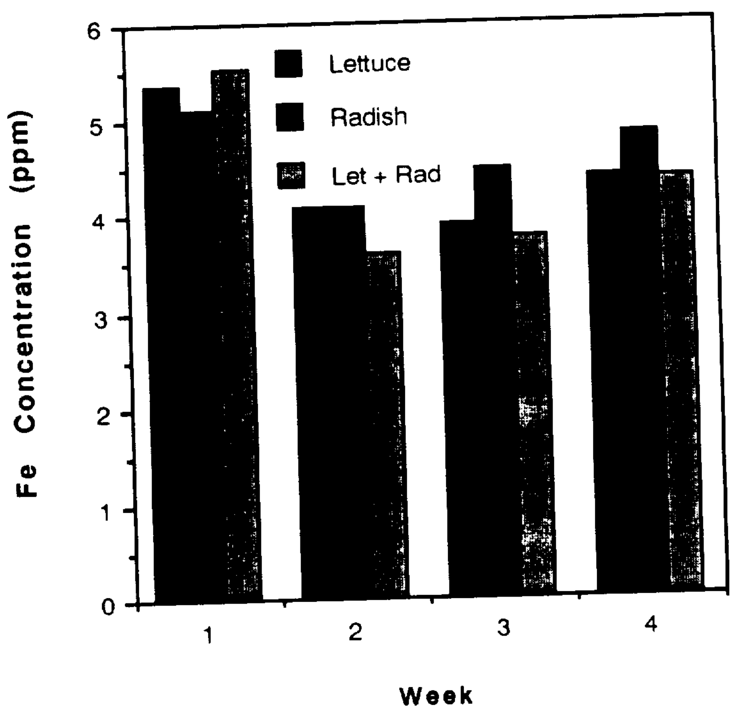


Fig. 10. Nutrient Solution Fe Levels, Exp2.



rapids lettuce grown under either 320 μmoles/m^2/s or 700 μmoles/m^2/s PAR from either metal halide or high-pressure sodium lamps. However,to know for certain what caused the observed difference in yield of these particular cultivars would require empirical testing.

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